

# Effects of Neutron Emission on Fragment Mass and Kinetic Energy Distribution from Thermal Neutron-Induced Fission of $^{235}\text{U}$

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**Abstract.** The mass and kinetic energy distribution of nuclear fragments from thermal neutron-induced fission of  $^{235}\text{U}(n_{th}, f)$  have been studied using a Monte-Carlo simulation. Besides reproducing the pronounced broadening in the standard deviation of the kinetic energy at the final fragment mass number around  $m = 109$ , our simulation also produces a second broadening around  $m = 125$ . These results are in good agreement with the experimental data obtained by Belhafaf *et al.* and other results on yield of mass. We conclude that the obtained results are a consequence of the characteristics of the neutron emission, the sharp variation in the primary fragment kinetic energy and mass yield curves. We show that because neutron emission is hazardous to make any conclusion on primary quantities distribution of fragments from experimental results on final quantities distributions.

**Keywords:** Monte Carlo, neutron-induced fission,  $^{235}\text{U}(n_{th}, f)$ , standard deviation

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## INTRODUCTION

Fragment mass and kinetic energy distributions from thermal neutron-induced fission of  $^{235}\text{U}(n_{th}, f)$  are ones of the most studied parameters since the discovery of the neutron-induced fission of uranium by Hahn and Strassmann in 1938 [1]. The objective was to understand the fission process between the saddle point to scission. Nevertheless, direct measurements can only be carried out on the final fragments (post neutron emission) mass yield  $Y(m)$  and kinetic energy ( $e(m)$ ).

For  $^{235}\text{U}(n_{th}, f)$  reaction, the mean value of kinetic energy  $\bar{e}$  and the standard deviation (SD) of the kinetic energy  $\sigma_e$  as function of the final mass  $m$  was measured by Brissot *et al.* [2]. The plot of the measured  $\sigma_e$  shows one pronounced broadening around  $m = 109$ , which is explained as a results of neutron emission from nuclear fragments. In a latter experiment, Belhafaf *et al.* [3], repeated the experiment of Brissot *et al.*, obtaining a second broadening around  $m = 125$ . They claim that this broadening must exist in the primary fragment kinetic energy ( $E(A)$ ) distribution.

In this paper, we present a new Monte-Carlo simulation results concerning  $^{235}\text{U}(n_{th}, f)$ . We show that the broadenings on the  $\sigma_e$  curve around the final frag-

ment masses  $m = 109$  and  $m = 125$  can be reproduced without assuming an adhoc initial structure on  $\sigma_E(A)$  curve.

## MONTE CARLO SIMULATION MODEL

In the process of  $^{235}\text{U}(n_{th}, f)$ , the excited composed nucleus  $^{236}\text{U}^*$  is formed first. Then, this nucleus splits in two complementary fragments. Assuming a linear dependence between kinetic energy and number of emitted neutrons, and taking into account that there is no neutron emission ( $\nu = 0$ ) for fragments having the maximal kinetic energy ( $E_{max}$ ) and that for the average value of fragment kinetic energy ( $\bar{e}$ ) the neutron number is equal to  $\bar{\nu}$ , the neutron number  $N$  as a function of kinetic energy results,

$$N = \text{Integer part of} [\alpha + \bar{\nu}(1 - \beta(\frac{E - \bar{E}}{\sigma_E}))], \quad (1)$$

where  $\beta$  define the maximal value of kinetic energy as  $E_{max} = \bar{E} + \frac{\sigma_E}{\beta}$ , and  $\alpha$  is used to compensate the effect of the change from a real number  $\nu$  to an integer number  $N$ .

## Simulation process

In our Monte Carlo simulation the input quantities are the primary fragment yield ( $Y$ ), the average kinetic energy ( $\bar{E}$ ), the SD of the kinetic energy distribution ( $\sigma_E$ ) and the average number of emitted neutron ( $\bar{\nu}$ ) as a function of primary fragment mass ( $A$ ). The output of the simulation for the final fragment are the yield ( $Y$ ), the SD of the kinetic energy distribution ( $\sigma_E$ ) and the average number of emitted neutron ( $\bar{\nu}$ ) as a function of final fragment mass  $m$ .

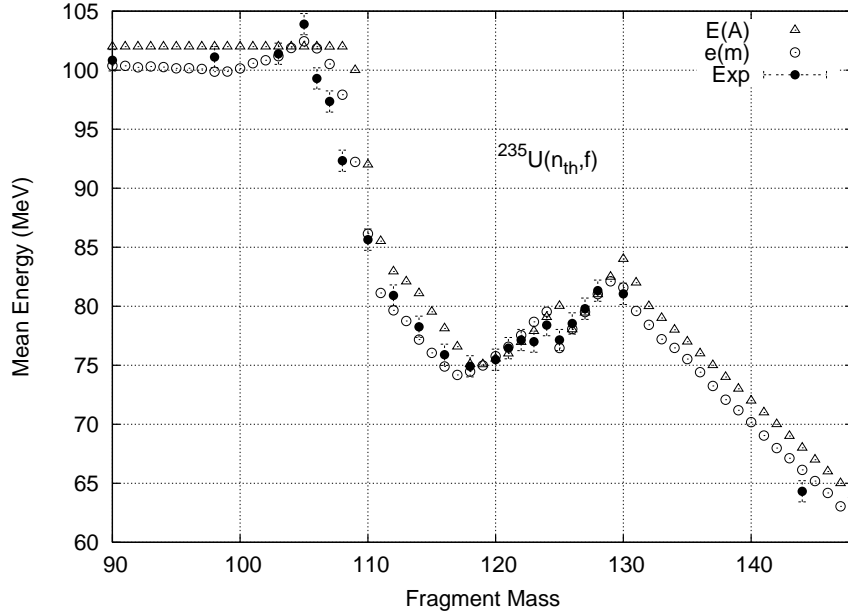
For the first simulation, we take ( $Y$ ) from Ref. [4],  $\bar{\nu}$  from experimental results by Nishio *et al.* [5], and  $\bar{E}$  from Ref. [3]. The first standard deviation  $\sigma_E$  curve is taken without any broadening as function of  $A$ . Then, we adjust  $Y(A)$ ,  $\nu(A)$ ,  $\bar{E}(A)$  and  $\sigma_E(A)$  in order to get  $Y(m)$ ,  $\bar{\nu}$ ,  $\bar{e}(m)$ ,  $\sigma_e(m)$  in agreement to experimental data.

In the simulation, for each primary mass  $A$ , the kinetic energy of the fission fragments is chosen randomly from a Gaussian distribution with mean value  $\bar{E}$  and SD  $\sigma_E$ .

For each  $E$  value, the simulated number of neutrons  $N$  is calculated through the relation (1). The final mass of the fragment is equal to  $m = A - N$ . Furthermore, assuming that the fragments loose energy only by neutron evaporation and not by gamma emission or any other process, and neglecting the recoil effect due to neutron emission, then the kinetic energy  $e(m)$  of the final fragment will be given by

$$e(m) = (1 - \frac{N}{A})E. \quad (2)$$

With the assemble of values corresponding to  $m$ ,  $e$  and  $N$ , we calculate  $Y(m)$ ,  $\bar{e}(m)$ ,  $\sigma_e(m)$  and  $\nu(m)$ .



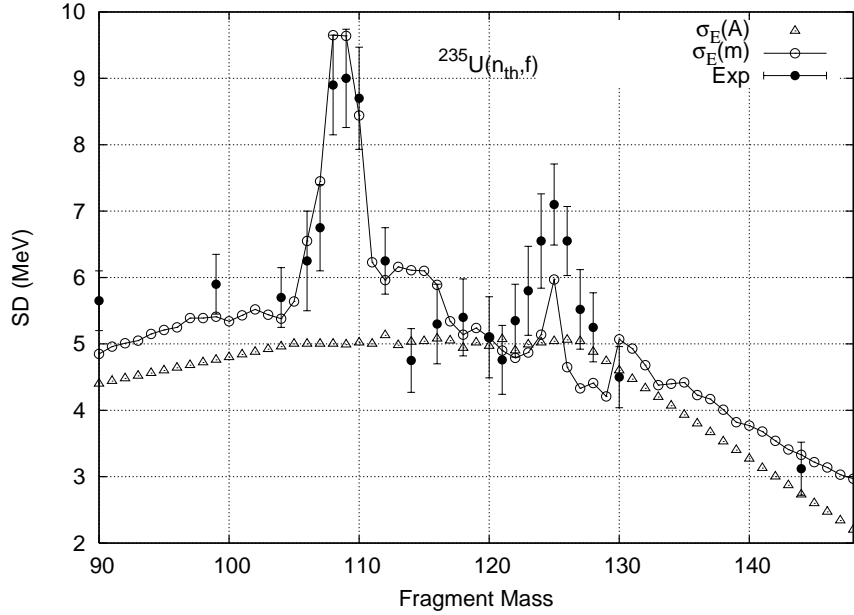
**FIGURE 1.** Mean kinetic energy of the primary ( $\triangle$ ) and final ( $\circ$ ) fragments, as a result of simulation in this work, to be compared to experimental data ( $\bullet$ ) from Ref. [3].

## RESULTS AND DISCUSSION

The plots of the simulated mean kinetic energy for the primary and final fragments as function of their corresponding masses, are shown in Fig. 1. In general, the simulated average final kinetic energy curve as a function of final mass ( $\bar{e}(m)$ ) have roughly a shift similar to that of  $Y(m)$  curve, and a diminishing given by relation (2) with  $N = \bar{\nu}$ . The exceptions of this rule are produced in mass regions corresponding to variations of the slope of  $Y(A)$  or  $\bar{E}(A)$  curves, for example for  $A = 109$ ,  $A = 125$  and  $A = 130$ .

Furthermore, Fig. 2 displays the SD of the kinetic energy distribution of the primary fragments and the SD of the kinetic energy of the final fragments ( $\sigma_e(m)$ ). The simulated results for  $\sigma_e(m)$  presented in Fig. 2 were obtained with  $\alpha = 0.62$  and  $\beta = 0.35$ . The plots of  $\sigma_e(m)$  reveal the presence of a pronounced broadening around  $m = 109$ , and a second broadening is found around  $m = 125$ , in a mass region where there are variations of the slopes of  $Y(A)$  or  $\bar{E}(A)$  curves. There is no experimental data around  $m = 130$ . Nevertheless, if one takes the experimental value  $\sigma_e = 3.9 \text{ MeV}$  for  $m = 129$  from Ref. [2] and one puts it on Fig. 2, the beginning of another broadening for  $m = 130$  is suggested. These results were obtained with a simulated primary fragment kinetic energy distribution without broadenings in the range of fragment masses  $A$  from 90 to 145 (see Fig. 2,  $\triangle$ ). If one simulates an additional source of energy dispersion in  $\sigma_E$ , without any broadening, no broadening will be observed on  $\sigma_e$ .

The presence of broadenings on  $\sigma_e$  about  $m = 109$  could be associated with neutron emission characteristics (approximately  $\bar{\nu} = 2$ ) and a very sharp fall in kinetic energy from  $E = 100 \text{ MeV}$  to  $E = 85.5 \text{ MeV}$ , corresponding to  $A = 109$  and  $A = 111$ , respectively. The second broadening is produced by a discontinuity of the curve  $\bar{E}(A)$  around  $A = 126$ ,



**FIGURE 2.** SD of primary fragment kinetic energy distribution ( $\triangle$ ) and SD of final fragment kinetic energy distribution ( $\circ$ ), as simulated in this work, to be compared to experimental data ( $\bullet$ ) from Ref. [3].

which is necessary to reproduce a similar discontinuity on  $e(m)$  around  $m = 125$ . We give emphasis to the shape of  $\sigma_e$  which increase from  $m = 121$  to  $m = 125$  and it decreases from  $m = 125$  to  $m = 129$  as occurs with experimental data.

## CONCLUSIONS

For  $^{235}\text{U}(n_{th}, f)$ , in comparison with the primary fragments, the final fission fragments have eroded kinetic energy and mass values, as much as to give rise to the appearance of broadenings in the SD of the final fragments kinetic energy as a function of mass ( $\sigma_e(m)$ ) around  $m = 109$  and  $m = 125$  respectively. These broadenings are a consequence of neutron emission and variations on slopes of primary fragments yield ( $Y(A)$ ) and mean kinetic energy  $\bar{E}(A)$  curves. From our simulation results, another broadening, around  $m = 130$ , may be predicted.

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